# PERSISTENT SPACE SITUATIONAL AWARENESS:

# DISTRIBUTED REAL-TIME AWARENESS GLOBAL NETWORK IN SPACE (DRAGNETS)

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## Abstract

In the decades since the space program first began, the United States has become more and more dependent on space across a broad spectrum of military, commercial, and civil applications. That dependence brings with it an inherent vulnerability, and recent evidence of the growing threat, combined with acknowledged gaps that exist in our ability to rapidly characterize and attribute attacks on our satellites results in a compelling need for a robust space situational awareness (SSA) capability. The Distributed Real-time Awareness Global Network in Space (DRAGNETS) is one solution that leverages the trend toward distributed, networked military capabilities that nanotechnology will enable within the next 20 years. The DRAGNETS approach uses distributed constellations of thousands of very small sugar cube-sized "femtosats" to maintain continual cognizance of the space environment. Current and future advances in nanotechnology will lead to substantial miniaturization of satellite functions and allow the Air Force to field flexible, adaptive, and responsive systems as part of an overall SSA architecture. In order to realize the DRAGNETS vision, the Air Force should plan phased investments leading to an operational assessment of a prototype DRAGNETS constellation at a technology readiness level of 7 by 2025. The end result will be a capability that, when integrated with existing ground and space-based SSA assets, provides Combatant Commanders and senior decision makers with the necessary awareness to preserve maximum flexibility in the use of US space capabilities.

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## INTRODUCTION

Former Air Force Space Command (AFSPC) Commander Gen Lance Lord (USAF Ret.) defined space situational awareness (SSA) in simple terms: "The foundation of Space Superiority is Space Situation Awareness, which means having a complete understanding of what is happening in space."[1] What exactly does that mean? Gen Lord goes on to say in his 2005 article in *High Frontier* that "It is no longer sufficient to simply know where a satellite is in space. We must know what the satellite is capable of doing, what it is being used for and what it may be used for in the future."[2] Today the United States has a tremendous investment in space in our military, intelligence, scientific, and commercial sectors. Our space capabilities greatly influence everything we do. However, one of our most important space vulnerabilities is our lack of persistent situational awareness of the space operational environment to ensure we have freedom of action. As AFSPC Commander Gen Kevin Chilton stated in a 2006 media roundtable event at Peterson AFB, "We have been really good in the past at counting what's up there and keeping track of what's up there…I maintain it's time that we move beyond cataloging…to be able to identify what's up there and understand what it's mission is and then ultimately determine intent."[3] His vision is to gather this information sometime within an object's first orbit. But what if we could do it in real time? What kind of persistent, responsive, and adaptable capability would we need? Consider the possibility of having eyes and ears on orbit where the events are unfolding.

Under the auspices of the Air Command & Staff College Blue Horizons program, the focus of this research is to address these questions with an eye toward the possible in the year 2025. Specifically, this paper offers the Distributed Real-time Awareness Global Network in Space, or DRAGNETS, an approach that departs from the traditional paradigm of large,

specialized, one- or few-of-a-kind space-based surveillance satellites. Instead, consider an interconnected network of very small centimeter-scale "femtosat" satellites proliferated throughout a variety of orbital regimes, where each femtosat is a sensing node contributing to a greater common operational picture. In addition to providing indications and warning, these nodes can autonomously form clusters in the constellation with enhanced aggregate capabilities to collect more detailed information on objects or events of interest, sharing that information throughout the rest of the network and giving commanders in the space operational environment immediate situational awareness. The idea of using clusters of small satellites in missions traditionally relegated to large, complex, monolithic spacecraft is not new.[4,5] What is unique about the DRAGNETS approach is the aggressive focus on miniaturization of the elements and their use in an adaptive, global SSA constellation. A brief description of the methodology and structure of the discussion will help frame the approach.

The DRAGNETS story will follow a logical flow beginning with a short discussion of the compelling need for the capability. The paper will identify the realities of our dependence on space today and the trends for the future while highlighting the threat environment and existing SSA gaps. With this context in hand, the discussion will transition to a detailed description of DRAGNETS at an operational concept level then delve into the details of the technological advances required and the feasibility of achieving them. Specifically, the paper focuses most heavily on the role of nanotechnology as an essential enabler for DRAGNETS, describing areas of focus for further development. In addition, it explores the influence of global nanotechnology market trends and public perception on the pace of development in order to provide a snapshot of the environment in which Air Force strategic planning will take place. Finally, the paper concludes with a set of investment strategy recommendations in the near, mid and far terms. In

order to properly set the stage, the story begins by examining the context that drives the need for an approach like DRAGNETS.

## BACKGROUND: A STORY OF COMPELLING NEED

### U.S. Dependence on Space

It is perhaps an understatement to say that the United States is a space-dependent nation. The prevalence of telecommunications and navigation services alone used by government and private sectors speaks volumes to the already high and growing importance of this medium on every aspect of our daily lives. If there is any question of this, one need only to look back to May of 1998 when PanAmSat Corporation's Galaxy 4 satellite failed on orbit, resulting in the loss of pager service to some 40-45 million pager customers as well as the loss of service to many ATMs, credit card processing machines, and television stations – and that was nearly 10 years ago.[6] More recently, Lt Gen David McKiernan as the Operation Iraqi Freedom Combined Forces Land Component Commander stated that space capabilities "allowed me to talk via tactical satellite communications and other means across a battle space of hundreds of miles…it allowed us to make decisions and then execute those decisions faster than any opponent."[7] US Strategic Command Commander Gen James Cartwright added emphasis in a 2005 statement before the Senate Strategic Forces Subcommittee on Space Policy: "The US economy, our quality of life, and our nation's defense are all linked to our freedom of action in space."[8] But we're not alone.

### The Potential Threat

Europe, Russia, China, Japan, and a handful of others have long been our cohabitants in space, and that trend is spreading as international cooperation and transnational commercial ventures provide means of access to non-traditional partners in other parts of the world such as

Southeast Asia and Africa. Some of these state actors recognize our dependence on space and see potential strategic vulnerabilities. Defense Intelligence Agency Director Lt Gen Michael Maples stated before the Senate Select Committee on Intelligence recently that "several countries continue to develop capabilities that have the potential to threaten U.S. space assets, and some have already deployed systems with inherent anti-satellite capabilities."[9] In an emphatic coincidence, China launched an anti-satellite missile that destroyed a Chinese Fengyun-1C weather satellite during a technology demonstration on the same day as Lt Gen Maples' SSCI hearing.[10] Additionally, the 2001 Space Commission Report identified micro- and nanosatellites in the 100 kg down to 10 kg size range as a growing class of threats to our space assets. According to the report, such miniaturized platforms could be "placed on an interception course and programmed to home on a satellite…[to] fly alongside a target until commended to disrupt, disable, or destroy the target."[11] So how can we detect these threats in advance?

**A Space Situational Awareness Capability Gap**

The existing Space Surveillance Network consisting of some 30 or so ground-based sensors around the world along with the orbiting Midcourse Space Experiment (MSX) provides the vast majority of our SSA capability, a capability Gen Chilton emphasized earlier was limited to counting and cataloging space objects. Key coverage gaps include an inability to adequately monitor and characterize events occurring out of view of the ground sensors, weather-dependent optical viewing, a lack of high-resolution signature and imagery data particularly at geosynchronous orbits,[12] and a capability to perform high-fidelity wide-area searches for small objects.[13] According to Jeffrey Morris in Aviation Week, AFSPC's future programs plan contains only one space-based SSA program over the next 25 years for timely coverage of high interest objects: an orbiting telescope known as the Space Based Surveillance System.[14] Even

considering this additional SSA system, a capability gap clearly exists for handling the kinds of threats identified by Lt Gen Maples, the Space Commission, and a host of others.

### The Compelling Need

In the calculus of strategic planning for our future space requirements, the combination of a growing US dependence on space, the increasing opportunities for threats to our space assets, and the existing situational awareness gap point to a compelling need for a robust SSA architecture. The DRAGNETS concept represents a new way of thinking about the problem in order to greatly enhance that architecture. Above all else, this research product is meant to generate ideas and discussion on the merits of thinking small when it comes to SSA. Having identified the compelling need, the next step in the story is to explore DRAGNETS in detail.

## DRAGNETS CONCEPT

### Overview

In the future, progress in nanotechnology may allow for the packaging of SSA capabilities into smaller and smaller satellites. This in turn will enable the establishment of vast constellations of low-earth and geosynchronous orbiting femtosats operating as interconnected sensing nodes on a network. As alluded to earlier, the term femtosat refers to spacecraft with dimensions of roughly a centimeter and less than one tenth of a kilogram.[15] These nodes can respond to objects of interest such as foreign satellites, co-orbital anti-satellite threats, or anomalous debris by "condensing" into localized groupings or clusters of femtosats to perform higher fidelity characterization while at the same time cueing other specialized SSA assets for further investigation. Such a network will provide high temporal and spatial resolution situational awareness of the space environment to support a host of missions including space object surveillance and identification, debris field mapping, technical intelligence collection, and

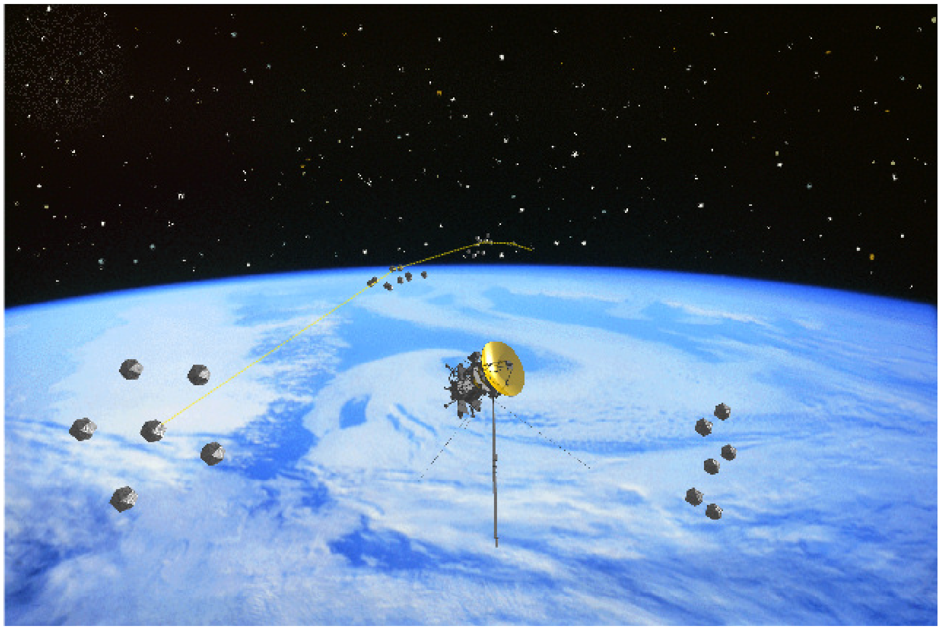

**Figure 1 DRAGNETS clusters investigating a suspect spacecraft and communicating that information throughout the constellation. (Illustration by author, "suspect spacecraft" model courtesy NASA/JPL-Caltech).**

space weather monitoring. The benefits of distributed networks of very small satellites extend beyond the missions they enable, however.

In addition to the characteristics mentioned above, the distributed femtosat concept also has several practical advantages. Due to their small size and simple structure relative to traditional spacecraft, femtosats lend themselves to rapid, low-cost mass production analogous to microelectronics fabrication today. System level environmental and functional testing of the individual femtosats, at approximately the size of a sugar cube, is inherently orders of magnitude easier from a process and logistics standpoint than today's medium class 2,500 kg satellite. Now consider the launch options.

At a conservative rough mass estimate of 10 g per femtosat, a constellation of 250,000 femtosats comprises the same launch mass as our medium class satellite. That constellation could place clusters of 10 femtosats spaced every 1.7 km at a 600 km low earth orbit (LEO) altitude. Alternately, the constellation could be constructed incrementally using excess launch

vehicle capacity on military, intelligence, NASA, or commercial missions. Finally, replenishment and upgrade of the constellation capability could be accomplished simply by replacing individual femtosats or through wholesale replacement of clusters. The preceding discussion of the capabilities and advantages begs a more detailed look at the inner workings of the DRAGNETS concept.

**DRAGNETS Elements**

DRAGNETS consists of three principle elements by which the concept may be described: the femtosats themselves, the constellation, and the command and control, or $C^2$. The femtosats can fly in 'wolf packs' as needed in order to surround an object to investigate from multiple perspectives. Building from here, the femtosats and their clusters are part of a constellation operating in a particular orbital regime, perhaps a specific altitude at a given orbital inclination, with multiple constellations needed to cover the full spectrum of missions. The architecture would also require a small number of relay satellites necessary for forwarding data streams to the ground stations and command uploads back to the femtosats. Finally, the $C^2$ element includes the aforementioned relay satellites, the unmanned remote ground stations, and the manned ground control center where the constellation mission data and situational awareness information are reviewed. The focus now turns from the DRAGNETS elements as defined above to a notional concept of operations (CONOP) in the form of a vignette.

**Concept of Operations**

The following hypothetical example serves as a business case for viewing how DRAGNETS might support the space warfighter of the future. Country X launches a medium sized 2500 kg satellite into a LEO as part of a well-publicized science mission. By all accounts in the open press, the satellite has a commercial remote sensing payload and a suite of antennas

for space weather analysis. However, as soon as the satellite is dropped into its LEO insertion point, a nearby DRAGNETS cluster detects the satellite with a combination of visible and infrared cameras as well as sensitive magnetometers and begins to quietly monitor the seemingly benign spacecraft.

Fifteen minutes after launch the small upper stage engine has cut off and separates along with the payload adapter from the satellite. A few minutes later when the satellite, spent upper stage, and payload adapter are out of view of the US Space Surveillance Network (SSN) ground assets, three small eight-inch cube objects separate from the payload adapter and drift away. The DRAGNETS cluster observes the covert dispensing of the microcraft and relays the information immediately, passing along not only the video and still images of the objects but also any state vectors of their motion. With access to a networked ground database of all known orbiting objects with current orbital elements, the DRAGNETS constellation autonomously determines over the next few minutes that the three microcraft are entering separate co-orbital tracks with three high-valued DOD satellites and cues the appropriate clusters to closely monitor the microcraft. The constellation sends out a priority message as an alert to all DOD and National satellites on the network and transmits the information to ground, allowing for cueing of the high-frequency, narrow spot beam SSN S-Band radars. With this information in hand, the operations director, and by association the key decision makers, have visibility into these events within minutes rather than waiting for several orbits to pass in order to build up statistical evidence of the anomalous objects from ground sensors.

Meanwhile, a cluster of several femtosats is taking up position within 1 km of one of the microcraft and begins a focused interrogation of the object. Several of the femtosats maneuver into position to get different simultaneous views with visible and infrared sensors, both passive

and active (using laser returns). Additional data collectors could be added as necessary to provide other high-valued information on the objects using other novel collection methods. The orbital altitude of this microcraft is slightly lower than that of the cluster, so as the microcraft moves away, the next cluster in the track is alerted and begins its surveillance. At the same time, a Space Based Surveillance System satellite has been cued to the position and heading of the microcraft in order to bring its specialized telescopes to bear.

The previous vignette leaves out many of the operational details but it provides an idea of how the DRAGNETS system would operate as part of an integrated SSA architecture. In order to take full advantage of the benefits of a distributed situational awareness approach, many of the functions we associate with SSA and spacecraft in general will need to be significantly reduced in size, perhaps even combined within multifunction subsystems, while simultaneously improving the capacity. The path toward this goal leads through advances in nanotechnology, prompting a discussion of this emerging field and its impact on DRAGNETS.

## THE ROLE OF NANOTECHNOLOGY

The ability to package SSA tools into such small satellites in the future will depend on how well we can miniaturize and integrate the necessary satellite functions. Conventional satellite design processes generally classify these functions into eight critical subsystems: propulsion, attitude determination and control system (ADCS), communications, command and data handling (C&DH), thermal, power, structures, and, of course, the payloads.[16] Key to the reduction in size, weight, and power for these subsystems is a class of technologies known as nanotechnology. In order to better understand how nanotechnology will enable the femtosat concept, a basic definition is in order.

## What is This Nanotechnology Stuff, Anyway?

The "nano" in nanotechnology refers to the size scale of the scientific phenomena applied to create these technologies. This prefix refers to length scales of one billionth of a meter, in the size neighborhood of an average molecule, and the nanoparticles upon which nanotechnologies are built range in dimensions from a few to several hundred nanometers. By comparison, the human red blood cell is 6,000 nanometers.[17] Therefore, nanotechnology is a broad umbrella term referring to the application of nanoscale science where the materials have some rather unique characteristics. As an example, carbon nanotubes, which were discovered in 1991, are a special form of carbon that has "100 times the strength of steel, conduct heat better than a diamond [itself one of the best thermal conductors in the world], and carry electricity better than copper."[18] The unique properties of nanotechnology will play a critical role in enabling the DRAGNETS system at each level, from the femtosats to the constellations and their $C^2$.

## Application to DRAGNETS

At the femtosat level, the most important benefit from nanotechnology will be the significant reductions in size, weight, and power requirements for each of the functions mentioned earlier. In the year 2025, these functions will also be combined in multi-role subsystems such as cameras that are dual-use as star trackers for attitude determination, or reconfigurable elements like laser transceivers able to tune to different frequencies appropriate for either laser imaging or communications tasks. As computational speed grows, the autonomy of the satellites will improve and much more on-board data processing will occur, placing less demand on the communications architecture for raw data transmission. These computational advances have implications at the constellation level, too.

Constellations of femtosats will operate with a degree of self-awareness supported by the

nanotechnology-enabled processing power and networking technologies projected to evolve over the next two decades. Without intervention from the ground, the system will continuously monitor its own state of health, identifying failing femtosat elements. The constellation will then perform corrective measures itself, signal to ground for instructions, or deactivate and remove the faulty elements. Similarly, the architecture will respond to external events by adapting to focus more attention on the event while passing along all relevant information to different regions of the constellation, other satellites on the network, and the ground $C^2$ nodes. An architecture this complex would quickly overwhelm today's $C^2$ capabilities, but our 2025 ground segment will be reaping the nanotechnology rewards too.

As stated in the National Nanotechnology Initiative (NNI) report *Nanotechnology in Space Exploration*, there will be a critical need "to transition the present mission operations paradigm of many humans per vehicle to many vehicles per human."[19] Recall the scope of the problem: 10's or 100's of thousands of femtosats per constellation constantly monitoring and adapting, some providing event reporting, while others are streaming environmental measurements, debris characterization data, etc. Although the substantial on-board computing described above will alleviate some of these challenges, there will also be vast improvements in the ability of the ground control system to handle the workload. Computational power and orders of magnitude higher data storage densities will be married to new techniques for interaction between the human and the machine, resulting in a much more efficient ground element with only a handful of people operating the constellation.

The next step in this discussion is to explore in detail four key functional applications of nanotechnology most likely to impact the DRAGNETS system: propulsion, sensors, power, and data processing. Each of the following four sections will look at current trends in

nanotechnology in those a ... dvances and the prospects for evolution to a DRAGN ...

**Propulsion**

As mentioned earl ... will need to rely on some very non-traditional appro ... control or to modify their orbits. The femtosat o ... ology variant of electric propulsion[20] due to the i ... s, referred to as specific impulse, or $I_{sp}$.[21] One p ... h-efficiency operation on larger satellite systems is the field effect emission propulsion, or FEEP thruster ...

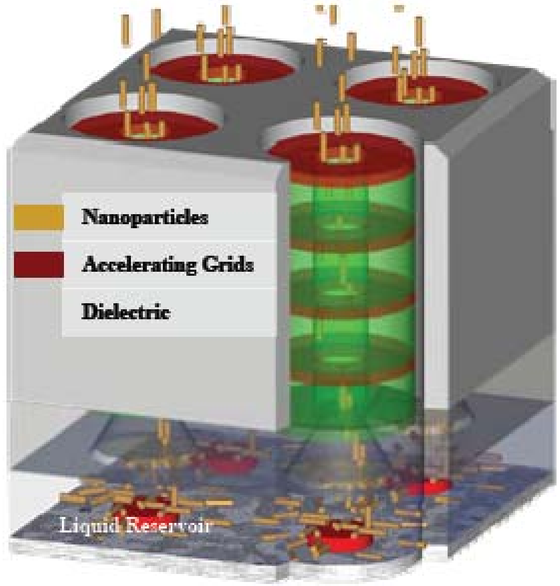


**Figure 2 Researchers at the University of Michigan propose using variable-size carbon nanotubes in a field effect thruster to achieve tunable thrust levels. (Reprinted from Musinski et al, "Nanoparticle Electric Propulsion: Experimental Results." In *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit.* Sacramento, CA, 2006).**

an accelerating grid and a liquid or solid substance from which ions or electrons can be extracted. In a FEEP, an extractor grid forms an electrostatic potential that, when highly concentrated, can actually pull ions and electrons from the surface of the working solid or fluid. The individual components are on the micron (one millionth of a meter) scale and can be produced in varying sized arrays up to a few centimeters in dimension using standard semiconductor fabrication techniques. Liquid Indium FEEP's have been demonstrated using with $I_{sp}$ values as high as 10,000 seconds and thrust efficiencies over 90%,[22] meaning over 90% of the input energy is converted into propulsive energy. By comparison, the most common chemical combustion thrusters in use today perform with an $I_{sp}$ of around 300 – 400 s.[23] The challenge with FEEP thrusters is that although they are highly efficient at low-thrust operation, the power requirements needed to achieve high thrust levels for quick reaction adjustments is impractical for a femtosat.

Researchers at the University of Michigan are investigating a FEEP-like thruster that

proposes to use carbon nanotube rods floating in a host fluid in lieu of pulling the ions from the surface of that fluid. The advantage is lower required electric field levels, leading to lower power levels, and the size of the carbon nanotube (CNT) rods can be tuned for variable thrust levels.[24] This tuning allows on-orbit throttling for either low thrust formation flying and station keeping or high thrust orbit adjustments. The concept is currently at a technology readiness level (TRL) of 2-3 based on limited component level testing performed to date,[25] while its more mature FEEP cousin has been assessed at TRL 4-5.[26] It is clear then that several areas will require focus in the coming years to meet the femtosat propulsion system challenges.

Bridging the application gap to get the propulsion system down to an acceptably small size will require advances in the development and integration of nanoscale thrust sources with a robust focus on modeling and simulation to understand how these devices will operate. Based on progress to date in this area, the underlying technologies described above will likely mature to TRL 6-7 within the next five years and a variable thrust nanopropulsion system ready for integration into a prototype vehicle should appear on the horizon in 10 years. However, the AF will need to provide motivation for further miniaturization of the subsystem since the present focus in commercial and civil applications appears to be scaled up arrays for use on small to medium class spacecraft. Another area expected to benefit from the "smaller is better" trend is the sensor subsystem.

**Sensors**

Sensors impact a number of functions in our femtosat concept, from camera systems that collect images of other objects, to star trackers and sun sensors that determine the spacecraft attitude. By the year 2025, nanotechnology will enable revolutionary improvements in sensor capability density, a figure of merit describing the data collecting power per unit volume of a

system. This section ( ... g cameras and attitude determination sensors a ... TS vision.

Since the purpc ... ce objects, it stands to reason that progress in ... particular interest. The idea of collecting cm-cl ... nments from kilometers away using a sensor no ... t, but that is the class of

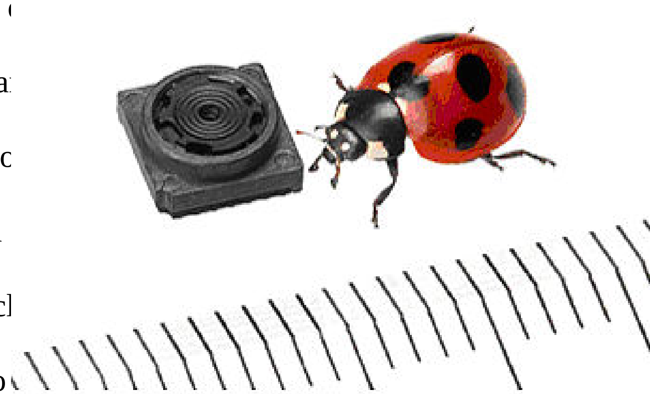

**Figure 3 The Sharp electronics company introduced this miniaturized camera in a March 2006 press release citing applications in next generation mobile phones. (Adapted from Sharp Corporation. "Press Release: Sharp to Introduce Industry's Thinnest, Most Compact 110,000-Pixel CMOS Camera Module; Optical System Only 1/11-Inch in Size." [accessed on March 10, 2007]).**

provide stepping stones in that direction. Based on the company's research, the SMPD sensor is 2,000 times more sensitive and half the area[27] of a conventional charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) sensors found in nearly all of today's space-based imaging systems, and the company is already marketing the technology commercially in the cell phone, security, and camcorder industries. Japanese electronics provider Sharp also announced a miniaturized camera for mobile phones using more mainstream technologies tightly packaged in a 5.5mm x 5.5mm x 2.4mm volume (see Figure 3).[28]

Quantum dots (QD) are another class of nanoscale photonic technology with applications for sensing. As a passive detector, they offer exceptionally low susceptibility to self-generated thermal noise. Another advantage is their extremely selective tunability to specific wavelengths of light.[29] Based on this property, they can be used as very efficient laser sources and paired with corresponding QD detectors in laser detection and ranging (LADAR) imaging systems. Attitude determination sensors will benefit from these sensitivity enhancements as well, but a bigger payoff is reducing their demand for surface space and spacecraft resources in favor of the mission payloads such as the sensors.


**Figure 4 Miniaturized sun sensor developed by NASA'a Jet Propulsion Laboratory and used as part of the KUTESAT-2 mission. (Reprinted from Sorensen et al, "KUTESAT-2, a Student Nanosatellite Mission for Testing Rapid-Response Small Satellite Technologies in Low Earth Orbit." In *AIAA 3rd Responsive Space Conference*. Los Angeles, CA: AIAA, 2005.)**

A 2002 Air Force Science and Technology Board report suggested trends toward system-on-a-chip (SOC) implementations will allow for substantially more efficient packaging of these attitude determination functions: "possible examples of spacecraft SOCs include sun and horizon sensors, inertial measurement units composed of MEMS [Micro Electro-Mechanical Systems] accelerometers and rate gyros, GPS receivers for navigation and attitude determination," among others.[30] Recent developments in nanotechnology point the way in the miniaturization of these functions. The Technical Institute of Denmark's Department of Micro and Nanotechnology reported in 2005 on the development and test of a chip-based 2-axis sun sensor measuring less than a centimeter across,[31] and NASA's Jet Propulsion Laboratory has fielded a similar-sized device (see Figure 4).[32] However, attitude determination sensors will need to shrink at least another two orders of magnitude (sub-millimeter) for DRAGNETS. A show of AF interest in this direction through small amounts of seed corn funding may be enough to spur research and development into the next generation of miniaturized sensors. In any event, these components need energy to operate, and the power subsystem will require advances of its own.

**Power**

Power is the lifeblood of a satellite, and striking the proper balance in devoting satellite volume and surface are to power collection versus mission capability is a delicate process. There are two ways to address this issue. The first is to develop other extremely power-efficient subsystems (loads). As mentioned previously, nanotechnologies will contribute to this by making packaging much more efficient, reducing the need for inherently lossy interconnects and improving electrical signal transmission by eliminating parasitic heat losses. The other way to address the problem is through the development of novel power generation and storage technologies to increase the specific power of the materials. In the DRAGNETS femtosat, both approaches will be needed, and this section focuses on the latter.

The two key aspects of the power subsystem are the power generation and power storage. In a typical satellite, the solar arrays and batteries play these roles, respectively. Future power generation techniques will either gather power from the environment (e.g. solar), or bring stored power in the form of fuel cells or radioisotope-based devices. Companies such as Evident Technologies and Konarka are currently developing QD-based solar cells with the ability to not only improve visible light conversion but also trap and convert infrared photons as well, taking advantage of a significant portion of the solar spectrum.[33] Other concepts identified for miniaturized use include alpha-voltaic cells with radioisotopes that emit high energy radiation into a semiconductor medium to convert the kinetic energy of the radiated particle into a current, offering greater than 90% conversion efficiencies and component lifetimes of decades.[34,35] Once the energy is created in the form of electrical current, it typically must be stored for later use and to assist in regulating its distribution throughout the satellite.

Storage mechanisms can broadly be classified as either batteries, operating on electrochemical processes, or capacitors, storing energy by maintaining a voltage between

separated electrodes. Batteries in our femtosat application will likely leverage nanostructures such as nanofiber electrodes and self-assembled nano-wells for the energy storage medium.[36] Supercapacitors are a promising alternative to batteries. The latest generation of these devices is currently under development at a laboratory benchtop level, incorporating the ubiquitous carbon nanotube (CNT) as an electrode material and enabling energy densities nearly eight times higher than the best capacitors available commercially today.[37] Their specific energies tend to be lower than those of batteries, but they've shown significantly higher numbers of discharge cycles with less degradation. Additionally, charge times measure in seconds versus minutes or hours for equivalently sized batteries, and they are well suited for rapid surge discharge applications. Supercapacitors based on these CNT structures are expected to be commercialized five years from now.[38]

The power technologies mentioned above are building blocks toward the performance DRAGNETS will demand. Significant momentum already exists to move these technologies along, and the focus of AF future investments here should be on the application side over the next 15 years or so in the area of integration of these devices into femtosat vehicles using SOC principles. Once the power supply challenges are solved, one of the most important users will be the data processing function.

**Data Processing**

If electrical power is the satellite's lifeblood, then the data processing system is its brain. As satellite systems of all sizes become more complex and are asked to do more through on-board number-crunching, the speed and efficiency of the processor becomes a limiting factor for mission achievement. The commercial market has driven the technology in this field, as long-standing rivalries between semiconductor giants Intel Corporation and Advanced Micro Devices

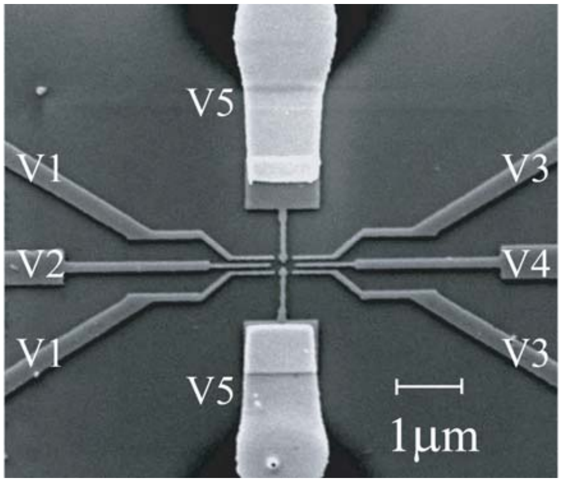


**Figure 5 Quantum computing experts believe quantum dot structures such as this double QD developed by Purdue University researchers will figure prominently in miniaturized, high-demand processing applications. The two QD's sit side-by-side as tiny gaps at the center of the picture. (Reprinted from Boutin, Chad. "Quantum Computers Are a Quantum Leap Closer, Say Purdue Physicists." Purdue News Service, [accessed on March 13 2007]).**

can attest. Whether the application is commercial or military, nanotechnologies will figure prominently in computing starting over the next decade. Processor speed and the distances over which the data signals travel are inversely proportional, so nanoscale devices will necessarily harvest tremendous gains in computing power.

In 2002, the Quantum Information Science and Technology (QIST) Experts Panel convened a quantum computing (QC) workshop in La Jolla, CA, in order to establish a working roadmap for QC technologies with a target horizon of 2012. The panel identified nine different technologies for further development and highlighted QDs as one of the most promising techniques for miniaturized QC applications.[39] The tremendous advantage of QC is due primarily to a phenomenon known as quantum superposition in which all possible outcomes of a given calculation on a given set of input values are determined simultaneously. Charlotte Barbier at the University of Virginia translates into layman's terms: "Because of this, a quantum computer has the potential to be $10^6$ [i.e. a million] times more powerful than current supercomputers."[40] The QIST panel estimates an integrated, all-electronic quantum computer

capable of handling simple problems should be available by 2012.[41] Fortunately, the DRAGNETS ground control system will be much less driven by the need to miniaturize, which widens the trade space for meeting the requirements of data processing and other computationally intensive $C^2$ functions.

Since much of the basic constellation management will be accomplished through on-board processing, the majority of ground processing work will focus on mission data consolidation, interpretation, trend analysis, and archiving, as well as product dissemination and flight software upgrades. In order to accomplish these tasks, there will be as much emphasis on reducing data transmission latencies as on processor speed. One of the biggest bottlenecks in ground processing architectures today is throughput: moving the data between points that need it to perform their functions, such as from memory to processor. The challenge for nanotechnology will be to reduce signal mismatches and transmission losses at the junctures between devices and shorten the distance signals need to travel between operations. There is much to be done, but the payoffs are potentially enormous.

It is clear from the foregoing discussion the femtosats' performance in a DRAGNETS architecture will only be possible with significant advances in the technologies identified. But is there a concerted effort in the scientific community to move research in the right direction? And is the capital there to support the research? Perhaps global market trends in nanotechnology can shed light on these questions.

## NANOTECHNOLOGY MARKET TRENDS

Nanotechnology is not new. Carbon nanotubes (CNTs) have been around as a known quantity for over 15 years, and their predecessors that go by exotic technical terms like "buckyballs" were identified two decades ago. However, it has only been in the last eight years

or so that the concept has picked up tremendous momentum as a hot research area with much to promise across many fields. In his foreword to the book *Nano-Hype*, former Nanotechnology Senior Advisor to the National Science Foundation Dr. Mihail Roco underscored this point: "While nanotechnology may be oversold in the short-term in some areas, its overall implications seem to be underestimated in the long-term."[42]

**Investment**

The Bush Administration recognized the growing potential for this class of technologies and its importance to a wide range of disciplines when it established the NNI in 2001. The purpose of the NNI was to facilitate public and private sector research and development into nanotechnologies.[43] Two years later Congress enacted and President Bush signed Public Law 108-153, the "21st Century Nanotechnology Research and Development Act" formally establishing a National Nanotechnology Program.[44] In 2006, nanotechnology was featured in the 2006 State of the Union Address as a cornerstone focus area for the President's American Competitiveness Initiative.[45] And the United States has followed up its commitments with resources as well: since its inception in 2001, the NNI program funding has increased from $464M to over $1.3B in 2006.[46] But the United States isn't alone in its nanotech interests.

In June 2005, Matthew Nordan from Lux Research Inc., one of the nanotechnology market's most widely consulted analysis sources, testified before Congress that 2004 global nanotech expenditures topped $8.6B. Furthermore, he projected that "new, emerging nanotechnology applications will affect nearly every type of manufactured good over the next ten years, becoming incorporated into 15% of global manufacturing output totaling $2.6 trillion in 2014."[47] Nordan also explained before the Research Subcommittee of the House Committee on Science that US dominance of the field is giving way to more aggressive foreign investment.

At present, the United States leads in absolute investment, nanotechnology-related patents issued, corporate research and development spending, and scientific publications, but now lags behind several other countries in total investment relative to purchasing power.[48] An August 2005 article in Foreign Direct Investment magazine described strong US competition from European and Asian countries but also highlighted some signs of cooperation as well, such as recent research agreements between China's Zhejiang University and California's International Institute of Nanotechnology.[49] All of these signs point to tremendous growth in the nanotechnology market in the coming decade—fertile ground indeed for the kinds of advances required to make DRAGNETS a reality. It is important to note, however, that progress in these breakthrough technologies comes with the requirement for due diligence with respect to environmental and public safety concerns surrounding them.

**Public Perceptions**

When new technologies appear on the public stage in their infancy, there is a natural human tendency toward mistrust by those not familiar with the particulars. If a given technology moves faster than the public's ability to accept them, a backlash can occur with detrimental effects on the pace of continued development. In the past, negative perceptions toward pasteurized milk, nuclear power, and irradiated meats led to their slow acceptance, and today genetically modified foods face a similar uphill battle.[50] In order to identify these concerns up front, the Bush Administration has made environmental, safety, and health analysis a key element of the NNI program from the beginning.

In 2006, the Nanoscale Science, Engineering, and Technology (NSET) subcommittee to the President's Council on National Science and Technology published a report from its Nanotechnology Environmental and Health Implications (NEHI) Working Group detailing the

areas of research required to “enable sound risk assessment and risk management decision making.”[51] The intent of the report was to provide guidance to researchers, producers, and users of nanotechnologies about gaps in our knowledge of the impact of these technologies on our health. It asks questions such as what are the risks of exposure for the worker, the consumer, the general public and the environment, and what are the effects of inhaling, swallowing, or absorbing nano-engineered substances. One of the interesting aspects of the NSET’s plan is to make the process as transparent as possible, incorporating input from “citizen and industry groups, academia, and other research entities…through workshops, public hearings, and other means.”[52] Of significance, recent studies indicate public mistrust can be mitigated through the availability of balanced information on the risks and benefits.

The Woodrow Wilson International Center for Scholars and The Pew Charitable Trusts co-sponsor the ongoing Project on Emerging Nanotechnologies to explore the societal aspects of nanotechnology. In September of 2005, they published a report titled “Informed Public Perceptions of Nanotechnology and Trust in Government” to highlight what Americans understand about nanotechnology, its applications, and the proper way to manage its risks.[53] The key findings pointed to a strong desire for public input on the decision making process, particularly with billions of dollars in Federal government expenditures at stake.[54] The report also identified a desire for government regulation of the technology while at the same time voicing mistrust of existing Federal regulation approaches, citing recognition of corporate influence over Congress and the White House.[55] In general, those surveyed were suspicious of the tendency for industry to forge ahead with the development and marketing of products before they are adequately tested.[56] The recurring theme, of course, is keeping the public informed and putting the proper controls in place to ensure responsible technology development.

Public perceptions of nanotechnology will not directly impact Air Force strategic planning, but science and technology managers should expect to see the aforementioned controls applied through the Federal acquisition process. Although the technologies themselves are new, the importance of considering environmental, health, and safety concerns are not. Environmental impact assessments will still be required as they have for decades, and Occupational Safety and Health Administration regulations will still apply, tailored to the specific needs driven by nanotechnologies. Ultimately, public awareness of the benefits of nanotechnologies will broaden as they begin to impact consumer products and health care, and the generally positive outlook toward these applications could spur stronger growth, benefiting concepts such as DRAGNETS.

## LIMITATIONS

In moving down the path toward incorporating DRAGNETS-like capabilities into our future SSA architecture, we should be aware of some of the more important limitations. While not exhaustive, the following discussion is meant simply to identify two key areas needing to be resolved beyond the basics of developing the enabling nanotechnologies. The first issue is radiation survivability, significant in light of the importance of electronic components in the femtosat design. The other is the challenge of debris management: what do we do with hundreds of thousands of little metal cubes when they reach end of life?

### Radiation Hardness

In contrast to what intuition might tell us about the 'vacuum of space', the space environment presents a continual stream of energetic particles bombarding the upper atmosphere and more importantly our satellites above it. High energy free electrons can become embedded in spacecraft surfaces and components, leading to electrostatic discharges (sparks) in sensitive

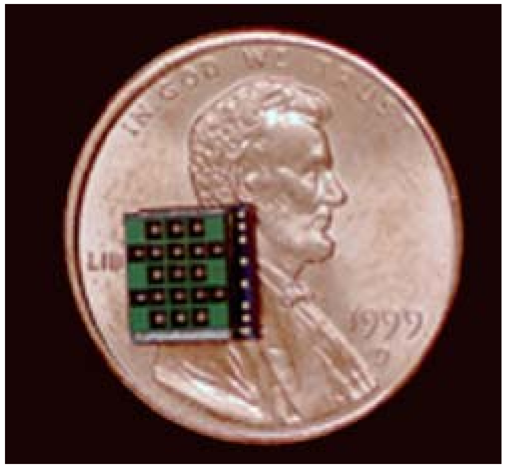

**Figure 6 Northrop Grumman prototype of a digital microthruster array. Devices such as this might be used as de-orbit propulsion sources to mitigate debris accumulation from dead femtosats. (Reprinted from Lewis, David. "MEMS/Micropropulsion." Northrop Grumman Corporation, http://www.st.northropgrumman.com/capabilities/space/propulsion/technologies/micropropulsion.html [accessed on March 17 2007]).**

equipment. Even higher energy particles such as those from solar flares can cause single event upsets (SEU's), manifesting as temporary or permanent component malfunctions. The extent to which a component is resistant to or shielded from these effects is its radiation hardness, and conventional techniques for hardening against energetic electrons and protons often involve shielding with aluminum or other absorbing materials. Since this approach is impractical in the DRAGNETS concept, it is worth exploring whether the properties of the nanocomponents themselves offer inherent radiation hardness.

Nanotechnology may offer solutions to mitigate this problem. One approach cited by the Air Force Science and Technology Board involves the use of vacuum integrated circuits, a modern twist on yesterday's vacuum tube. These devices operate by pulling current from a cathode by applying an electric field, a term known as field emission (if this sounds vaguely familiar, it's because field emission is the basis of the FEEP thrusters discussed earlier). Nanomaterials can be used to make long-lasting cathodes for integrated circuits to operate in "extreme temperature and radiation environments."[57] Another phenomenon working in our

favor is the fact that QD and CNT-based devices are also remarkably radiation resistant. According to a paper published at the *2nd International Energy Conversion Engineering Conference* in 2004, "QD/CNT-based photovoltaic devices have the potential to be as many as five orders of magnitude more resistant to radiation damage" than conventional electronic devices.[58] However, unless our satellite is made entirely of QD's and vacuum microelectronics, there is still much to be done in the analysis of space radiation effects on nanoelectronics.

**The End-of-Life Conundrum: Femto-Litter**

The other key issue to be addressed in the future is how to deal with the orbital debris resulting from failed femtosats. When these 10 g sugar cube-sized satellites die in our vignette altitude of 600 km, they become uncontrolled micrometeorites with roughly the same kinetic energy as a small car traveling 45 miles per hour.[59] Now multiply this by a few thousand femtosats. Clearly there has to be a fail-safe approach to eliminating this problem if DRAGNETS is to become a practical solution for SSA. The obvious choice is to provide some means for end-of-life de-orbit for LEO constellations and storage orbits for geosynchronous femtosats.

In order to assure end-of-life disposal, the propulsion method needs to be relatively 'dumb'. That is, it must be able to act mechanically or using a separate dedicated power source, either of which might be triggered by loss of femtosat power beyond some threshold duration. Recently, vaporizing liquid[60] and digital[61] (see Figure 6) microthrusters have been developed to provide simple, small sources of thrust for miniaturized applications. These thrusters run on minute micro-packages of propellant that ignite or vaporize by applying a small heat source and are ideal for use following a catastrophic system failure. The residual challenge, of course, is

how to tell the femtosat which direction to thrust if it is dead. Solving the radiation hardness and end-of-life disposal limitations of the DRAGNETS architecture are essential steps to attaining the vision of a distributed situational awareness capability.

## RECOMMENDATIONS

As discussed in the Background, there is a clear and compelling need to fill the gaps in our future space situational awareness architecture. The expense and difficulty of populating strategic locations on the earth's surface with new ground-based space surveillance assets coupled with the proven difficulty of producing large, complex satellites within the budgetary and schedule constraints required points to the need to think about the problem in a different way.[62] DRAGNETS offers one such approach, harnessing the power of "small" to address large problems. In order to make DRAGNETS a reality in the 2025 timeframe, the Air Force will need to phase its investment strategy appropriately in light of real-world fiscal and technical constraints as well as the current world-wide momentum toward nanotechnology development. The following sections provide recommendations on areas the Air Force should ***Lead*** and those they should ***Leverage***, looking ahead to the Near Term (2008 – 2014), the Mid Term (2014 – 2020), and Far Term (2020 – 2025). Finally, the section ends with areas for further research.

### Near Term (2008 – 2014)

The very first recommendation is to develop an overarching nanotechnology roadmap within the Air Force technology enterprise. Such a roadmap would enable the various science and technology elements (AFRL, AFOSR, AFIT, Air Force Academy, etc.) to cross-walk their basic research and application investment strategies while providing strong traceability back up through DOD to the National Nanotechnology Initiative (which funds DOD to the tune of $350M per year[63]). On the development side, the Air Force should leverage ongoing

commercial and academic basic research at the component level, taking full advantage of Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) opportunities to capture the ingenuity of those at the leading edge while continuing similar efforts at the research laboratories. One area the Air Force and commercial sectors stand to benefit from more than the academic is in manufacturing. The Air Force must ensure robust and level funding of nanoscale production technology development within AFRL's Manufacturing Technologies (MANTECH) program in order to provide a stable, long-term partnering incentive industry can plan for. Modeling and simulation will also be a critical need, particularly early on. Strong leadership and investment in a coordinated M&S effort will pay dividends down the road through better understanding of how to use these technologies in applications of interest to the AF.

**Mid Term (2014 – 2020)**

In the mid term the AF should plan to emphasize application-oriented efforts, leading the demonstration of femtosat subsystem performance in key areas such as image formation from ultra-small nano-enabled cameras at low light levels, hosting flight software packages on quantum computing testbeds, and integrating nano-enabled attitude control and propulsion systems. Constellation management and cooperative multi-vehicle SSA operations should be demonstrated on orbit using larger, mature nanosatellite platforms such as the CubeSat satellite bus.[64] By 2020 the AF should have integrated all femtosat subsystems and flown test articles to demonstrate functionality while establishing opportunities for early operational assessments. In parallel, the AF should leverage advances in nanotechnology-based supercomputing and artificial intelligence with an eye toward fielding highly efficient ground control architectures.

**Far Term (2020 – 2025)**

The final stage of DRAGNETS investment planning will drive toward an AF-led on-orbit demonstration of a distributed femtosat constellation. Important accomplishments will include simulating autonomous investigation of an uncooperative space object and sharing the information with other portions of the constellation, cueing other space-based and ground-based SSA assets, sending out test alerts to satellites with self-defense capabilities, and relay of data in near real time. The culmination of this stage of development will be a series of incremental operational assessment activities leading to a technology readiness level (TRL) designation of 7 rather than the TRL 6 traditionally identified for transition to an acquisition program. This may help reduce technology risks that seem to plague many of today's space programs.[65]

**Areas for Further Research**

Although this paper has focused primarily on the role nanotechnology will play in clearing many of the technical hurdles, a few other key areas require further research. In particular, an integrated, self-managed constellation of femtosats will rely heavily on advances in artificial intelligence for decision-making across a wide range of potential operational scenarios. Further investigation will provide an assessment of the requirements and risk associated with implementing autonomous operations in distributed satellite networks. The femtosats will also need an adaptive communications approach to efficiently share information among the other members of the constellation, other accessible satellite platforms, and the ground segment. Microsoft has sponsored work in this area for terrestrial wireless self-managed networks[66] and IBM has similarly funded research into autonomic computing.[67] Collectively, these efforts may provide a springboard for further analysis of the communications challenge.

## CONCLUSION

In the decades since the space program first began, the United States has come to depend on space as indispensable in many ways. That dependence, coupled with the growing threats of other actors seeking to deny the use of this medium, creates vulnerabilities that the United States is currently ill-equipped to address. The Distributed Real-time Awareness Global Network in Space (DRAGNETS) system comprised of constellations of thousands of miniaturized femtosats is a different way of looking at space situational awareness (SSA) than our current and future planned paradigm. Furthermore, DRAGNETS represents the natural convergence of the trend toward distributed, networked military solutions and the capabilities nanotechnology will enable over the next 20 years. This convergence will have significant cost and acquisition benefits, too.

Once the DRAGNETS design has matured to the point of transition to an acquisition program, the system will take advantage of substantial cost savings in several areas. The satellite-on-a-chip implementation lends itself to mass-production efficiencies that will allow entire constellations of femtosats to be produced in a very small fraction of the time it takes to integrate a large satellite from the ground up. Additionally, functional and environmental testing can be accomplished in a streamlined fashion compared to today's roughly year-long process, using much more cost-effective facilities and requiring far fewer paid workers to support. Finally, the launch options for a distributed system are very flexible, from single-launch insertion of entire constellations to incremental build-up using space-available services. In order to get to this point the United States will need to shepherd market enthusiasm and public trust.

Although significant leaps will be required in terms of the underlying technologies, we have the benefit of global market momentum on our side. The US National Nanotechnology Initiative and other publicly and privately funded efforts have contributed literally billions in

research dollars toward basic science and early applications, and the rest of the world continues to match our enthusiasm, if not yet our spending. In order to maintain that momentum, the US Government will need to take steps to ensure public confidence in its stewardship of this new area of technology. Although this will likely require additional health and safety measures in Air Force science and technology and acquisition efforts, the advantages of public support vastly outweigh the modest incremental overhead.

To make DRAGNETS a viable part of an integrated SSA architecture, the Air Force will need to properly phase its goals and investments. The very first step is for AFRL to lead an AF effort to establish and shepherd an overarching nanotechnology roadmap. In the 2008 to 2014 timeframe, investments should focus toward leveraging small business innovation while leading the charge in manufacturing and modeling and simulation technologies. By 2020, the AF should lead the integration and demonstration of femtosat-class spacecraft, make significant progress in constellation behavior and self-management research, and bring computational advances into the ground stations in order to realize significant efficiencies in ground control and data handling. Finally, the AF must target demonstrations of femtosat prototype constellations at both low earth and geosynchronous orbits to prove the capabilities in an operational environment by 2025. In taking these steps, the AF will put the right tools in the hands of our Combatant Commanders to preserve freedom of action in the space domain for the President and Secretary of Defense.

## APPENDIX A – TECHNOLOGY READINESS LEVELS

The following table spanning the next two pages provides DOD accepted definitions for hardware technology readiness levels and is extracted from the DOD Technology Readiness Assessment Deskbook.[68]

**Table 1 Technology Readiness Level definitions. Excerpted from the Technology Readiness Assessment (TRA) Deskbook, Department of Defense, 2005.**

| TRL | Definition | Description | Supporting Information |
|---|---|---|---|
| 1 | Basic principles observed and reported. | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties. | Published research that identifies the principles that underlie this technology. References to who, where, when. |
| 2 | Technology concept and/or application formulated. | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. | Publications or other references that outline the application being considered and that provide analysis to support the concept. |
| 3 | Analytical and experimental critical function and/or characteristic proof of concept. | Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. | Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed. |
| 4 | Component and/or breadboard validation in a laboratory environment. | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. | System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals. |
| 5 | Component and/or breadboard validation in a relevant environment. | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components. | Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals? |

| TRL | Definition | Description | Supporting Information |
|---|---|---|---|
| 6 | System/subsystem model or prototype demonstration in a relevant environment. | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. | Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| 7 | System prototype demonstration in an operational environment. | Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). Examples include testing the prototype in a test bed aircraft. | Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| 8 | Actual system completed and qualified through test and demonstration. | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications. | Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design? |
| 9 | Actual system proven through successful mission operations. | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions. | OT&E reports. |

## APPENDIX B – METHODOLOGY

This Appendix discusses the methods used to define the bounds of “the possible” for this research. Future technology projections are inherently uncertain, but the true value of going through the exercise is that it forces the author to look critically at what has happened in the past, what is happening now, and what that all means for tomorrow. It also engages the reader in thinking about the question at hand: the further out the forecast, the more equal the footing of the audience and the “subject expert”. And so the reader will probably view the projections with a critical eye, but at least he or she is reading it. A wide variety of methodologies exist, but I will focus on the two that were most important: Environmental Scanning and the Futures Wheel.

Environmental scanning is a technique that draws on research to build up a baseline of potential change indicators. Certain areas of a given field may change very slowly over time because of established, mature development processes and evolutionary progress. Other areas may signal a flurry of research activity that demonstrates not only increased interest, but also funding to pursue those interests. This can be one indicator of upcoming change. There are generally six strategies for scanning, although in truth they can be boiled down into three: expert panels, database literature review, internet surveys, hardcopy literature reviews, essays on issues by experts, and key person tracking. The literature reviews, internet surveys, and essays by experts are all variations on a theme involving investigation of written works on the subjects of interest to gain familiarity and identify the key focus areas. In the research for this paper, those four techniques played heavily.

Included in that is what I’ll refer to as “meta-scanning”, or reviewing the literature of expert futurists in the field. Similar to key person tracking, it involves looking at what “the experts” are projecting downstream, primarily as an investment planning product, and watching

to see if those projections are changing in any discernable way. The Lux Research products are the best example in this category. Lux puts a tremendous amount of effort into their recurring Nanotechnology Report, and the reports cost upwards of $4800 a copy. Needless to say, derivative research (reading what others say about the Lux Nanotechnology Report) is important here. The literature scans also played an important role in the modified Futures Wheel portion.

The Futures Wheel method is akin to brainstorming consequences. Select a trend or event and derive the associated secondary trends or events, then move down to the tertiary level and continue until you've exhausted the subject area or you've reached the fidelity or saturation desired. Mind Mapping is a closely related tool, and it's one that was particularly useful here. Using the FreeMind mapping tool, I was able to identify what I thought were important wildcards or external factors that would affect progress in nanotechnology over the next 20 years.

The first obvious factor was the global market for nanotechnology: what do the investment trends look like in both government and private sectors? Do the technologies ease into society through evolutionary products or will they hit fast and furious in a revolutionary way? Who's investing? Is it just DOD or is there significant venture capital and commercial interest driving the bus? Is the United States alone? What areas is the government investing in through the National Nanotechnology Initiative? By exploring these threads I was able to build up the impression of almost exponential economic growth in the nanotechnology sector based on the realization that public awareness is only starting to rise. Once nanotechnology goes mainstream in parallel consumer markets, the demand for these nano-enabled products pioneered in the small independent companies will fuel greater investments by the more conservative large companies seeking to ride the bow wave to profitability. Along the way I found the intersection

of this trend with public perceptions.

Investigating the role of the public in the government's investment policies, I found a number of surveys that documented mistrust by the public. That mistrust was placed at the doorsteps of both the Federal government and the industries who were perceived to be sacrificing public interest for corporate gain. The Vioxx fiasco was referenced several times. Apparently the Bush Administration took note of this and anticipated the need for scrutiny of the environmental, health, and safety aspects of working with nanotechnology and fenced a portion of the annual NNI budget for working these issues. Whether industry follows suit is another matter.

One area that quickly dropped out was the role of federal acquisitions policy. Specifically, a number of Congressional and GAO investigations have looked specifically at space acquisition programs and the dismal track records of the larger programs. I was expecting to devote a section to discussing how tightening of the acquisition reins might impact the DRAGNETS development. The conclusion I came to was not very much. The femtosat concept is such a different approach from the traditional satellite development that many of the normal spacecraft build-and-test perils don't apply once the system has progressed beyond a technology demonstration.

Consider the integration of the 4th satellite in a series of build-to-print spacecraft. Despite the fact that the design is mature, the process is so complex and the development still takes so many months or several years to complete that processes will vary, the program office evolves, regulations change, integration teams morph, etc. There's simply no way to hold all that constant. With the femtosats, once the design is mature, the production runs will take a matter of weeks or a few months to complete, will be largely automated, and can be functionally

tested with a minimum of human involvement. The one area that remains tricky is simulating the dispersed nature of a constellation in ground testing. In any event, Cost Schedule, and Performance will always be in tension, but when the schedules are so short, Mischief doesn't have much chance to come out and play.

As mentioned earlier, I found the Environmental Scanning and Futures Wheel techniques to be best suited for this research. Early attempts to pull in perspectives from subject matter experts in a Delphi Method panel analysis fell well short of expectations due primarily to conflicting schedules, out of office travel, and slow responses to queries. In the end, I was able to adapt each of the methods above as I learned more about the subsystem technologies involved, and the research gave me the opportunity to roll up my sleeves and dig into the details. This was probably the biggest payoff of all.

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[15] As a point of reference, the term “nanosat” has become common over the last decade or so for referring to satellites in the 10 kg down to 1 kg range, but it should be noted that in general, nanosats have very little to do with nanotechnology.  Additionally, “picosats” are now generally accepted to describe satellites in the mass range of 1 kg down to approximately a tenth of a kilogram.  Femtosats are envisioned to be the lowest rung on the size scale, capturing all satellites under 0.1 kg, or 100 g.

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[20] Satellites use propulsion to maneuver, whether for attitude control reasons or to modify their orbit. Most have chemical combustion thrusters that burn a gas or liquid fuel with an oxidizer much like a small rocket engine in order to control thrust. Some satellites employ electric propulsion systems such as Hall Effect thrusters that use electromagnetic forces to propel an ionized working gas in one direction and the satellite in the other.
[21] Specific impulse, or $I_{sp}$, is defined as the ratio of the thrust to the mass flow rate. It is a measure of how efficiently energy stored in the propellant is converted into thrust energy. Generally, high-thrust propulsion systems have low $I_{sp}$ and high- $I_{sp}$ systems have low thrust. The most versatile systems would have the capability to tune from very low- $I_{sp}$, high-thrust operation for orbit adjust maneuvers to high-$I_{sp}$ but low-thrust attitude control and station-keeping.
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